Magnets for Stellerators

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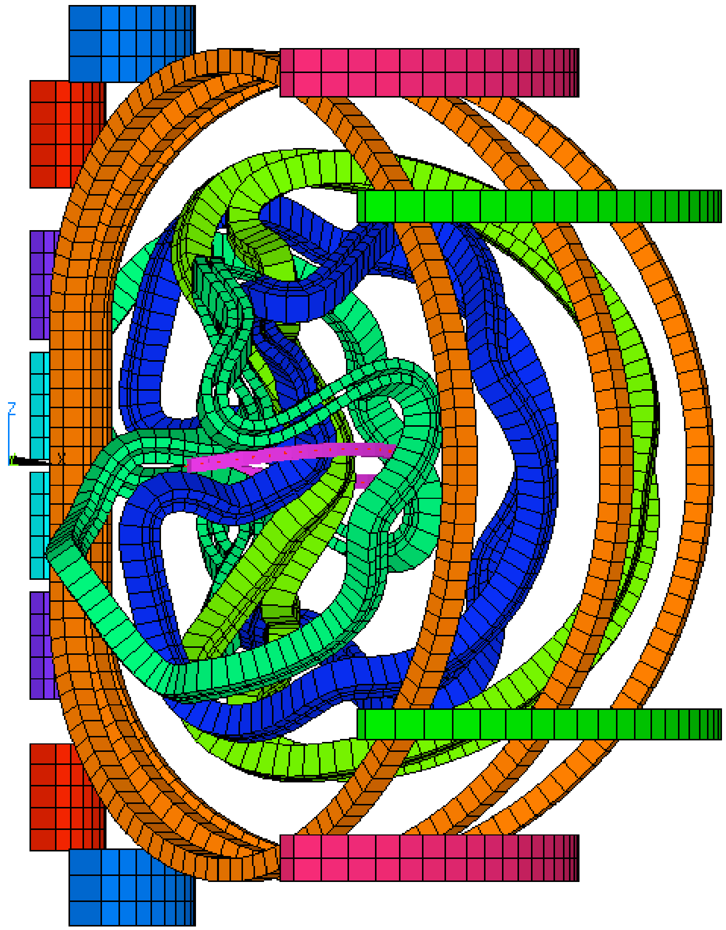
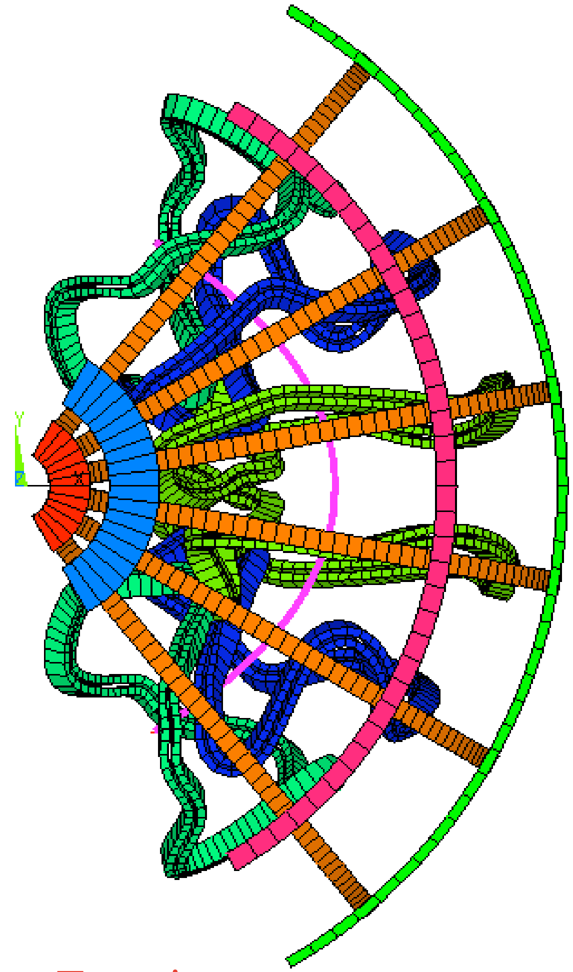
Stellerator magnets

- Topology of experimental magnets (using NCSX-like configuration)
  - Present magnet work concentrates on modular coils
- Insulation issues
- Topology of SC magnets for reactor
  - Advanced/aggressive technology
- Superconducting issues
- Structural issues
- Manufacturing

NCSX coils (from Han, PPPL)



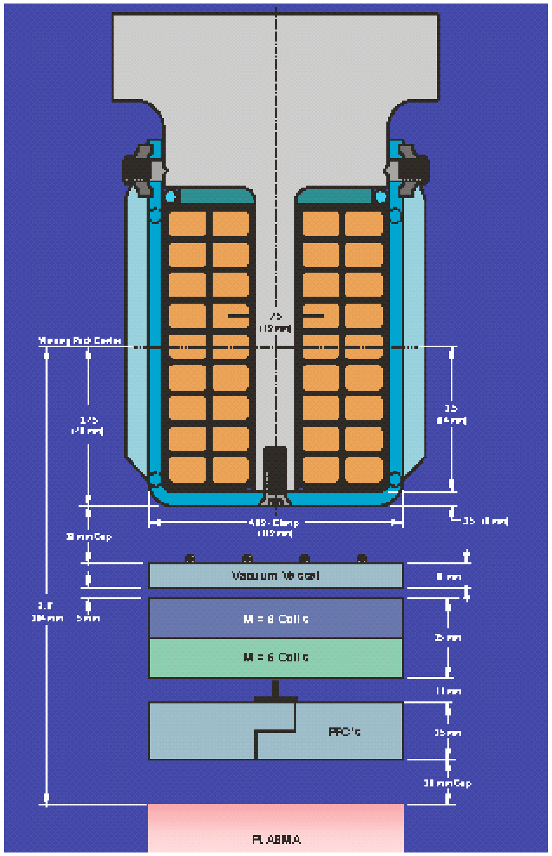
Side view



Top view

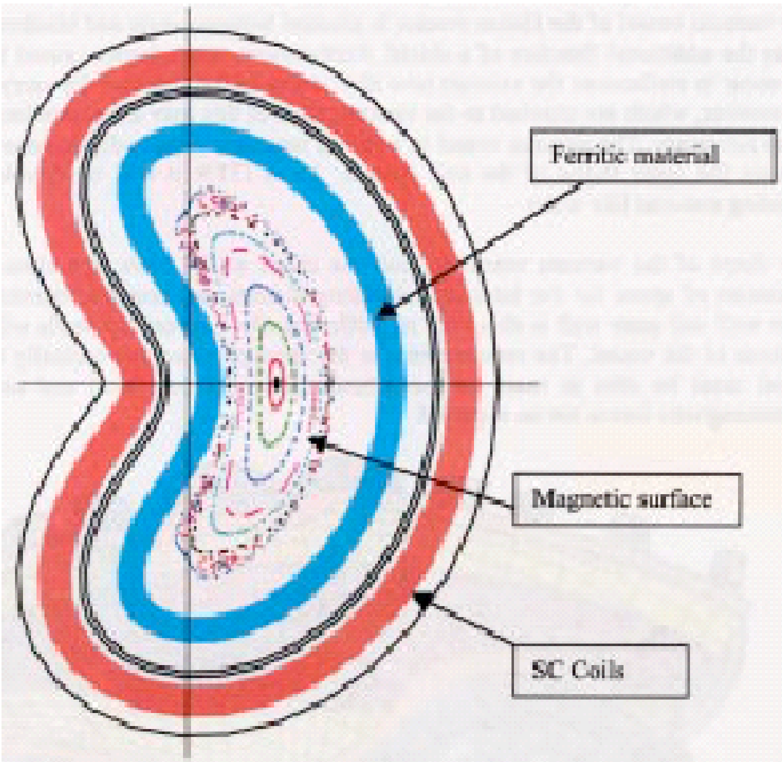
Topology-1

Modular coil construction of NCSX



Topology-2

Modular coils shape

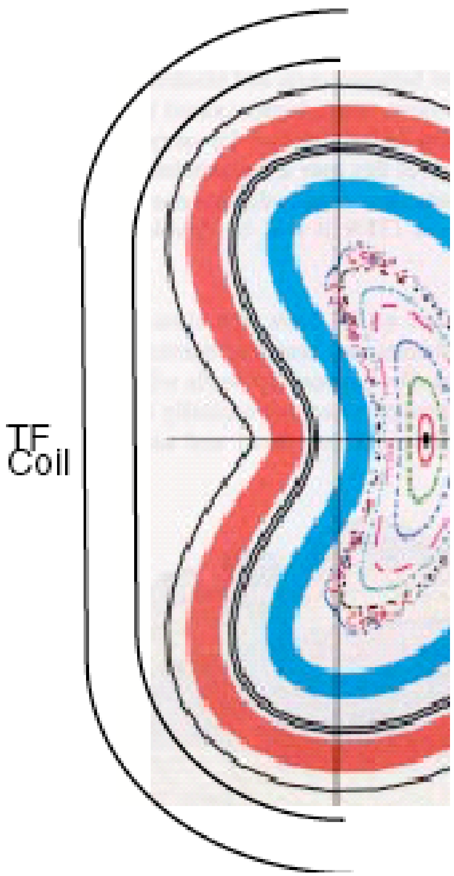


- Modular coils are very complex in toroidal direction, but rather "simple" in the poloidal direction
  - "Beans"
- Kink radius (r_c) in the toroidal direction drives design

Compact stellerator magnets

- Separate toroidal field coils from coils that provide “stellerator” fields
  - Does not result in increased magnetic field at the TF coil, since this is determined by the radial location of the region of the “bean”
- TF coils are simple, can tolerate high fields with high current density, can be further away from the plasma
- Possible to design modular coils that are not life-time components
  - Is this desirable?
- Discussions in this presentation will be limited to modular coils in this type of configuration
  - Goal is to provide code optimizers material needed for carrying out the optimization

Separate TF coil



- Field at TF coil is increased (vs integrated TF-modular coils) by gap needed for cryogenic shielding and assembly
- Can be addressed by design of cryostat
  - TF coil and modular coils can be placed in in same cryostat

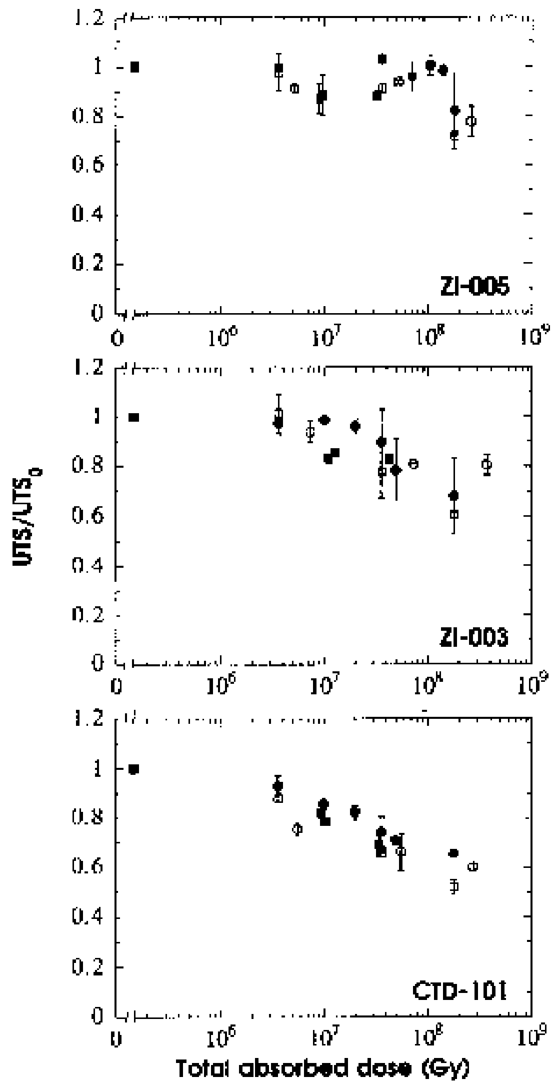


Figure 4 Normalized ultimate tensile strength of ZI-005, ZI-003 and CTD 101 as a function of total absorbed dose following room temperature irradiation with different reactor spectra (○, TRIGA, Vienna; ●, 2 MeV electrons; □, ^{60}Co-gamma rays; ■, IPNS, Argonne) and fracture at 77 K. UTS$_0$ is the ultimate tensile strength prior to irradiation

Type of irradiation

- Tests for irradiation of organics with e-beams, □'s, neutrons indicate that damage is due to power absorption per unit mass (rads, Grays)
  - Independent ot source of radiation.
  - Dependent on radiation dose rate!

Insulation consideration

Irradiation of organic insulation, 40 FPY (in MGray)

		Neutrons	Gammas	Total
ARIES-AT				
	Inboard	41	33	74
	Divertor	31	26	57
	Outboard	50	320	370
IFE-Flibe				
	1 cm gap	380	2480	2860
	0 cm gap	100	600	700

- Lightly insulated magnets have increased ratio of □'s to neutrons
- If radiation damage due to □'s is relevant (*i.e.*, organics), shielding requirements increase substantially, even for materials with comparable neutron radiation resistance

Issues of insulation

- Modular stellerator coils will likely be lightly shielded
  - To minimize distance between modular coil and plasma
  - Ratio of γ-dose rate to neutron flux larger than for well shielded magnets
- Damage to insulator drive shielding design when designing with organic insulators (because damage from γ's)
- Inorganic insulators would substantially increase the radiation tolerance of coils

Plate type modular coils

Shell

Radial plates

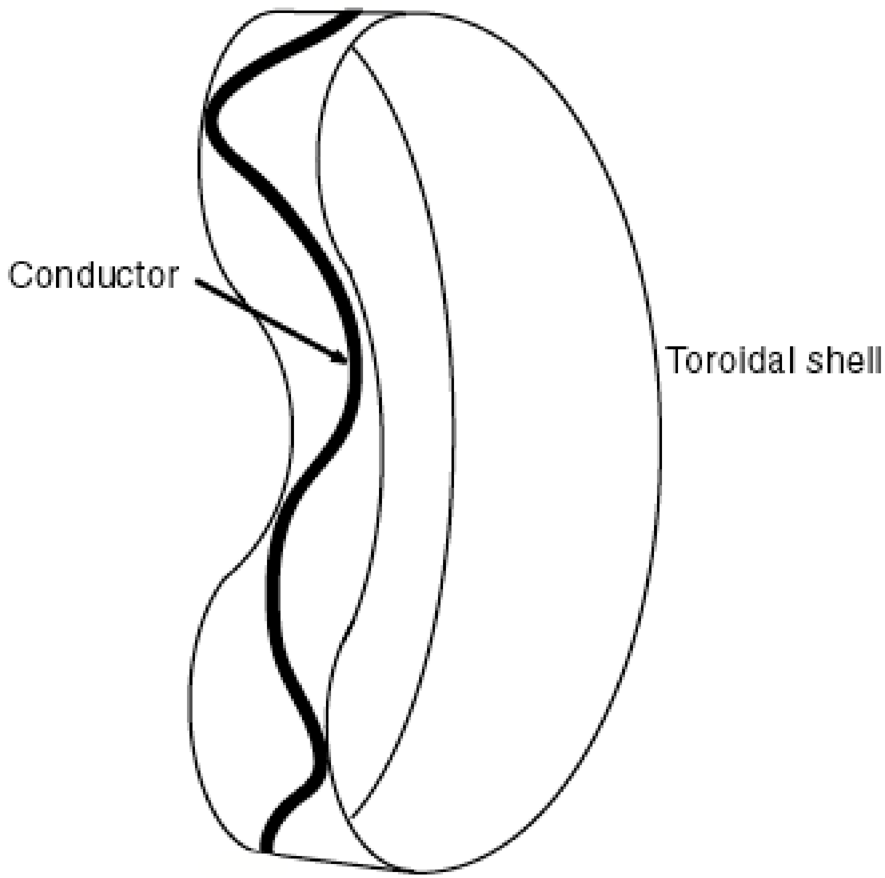
Hybrid plates

Modular coil design -1

Choice of modular coil construction

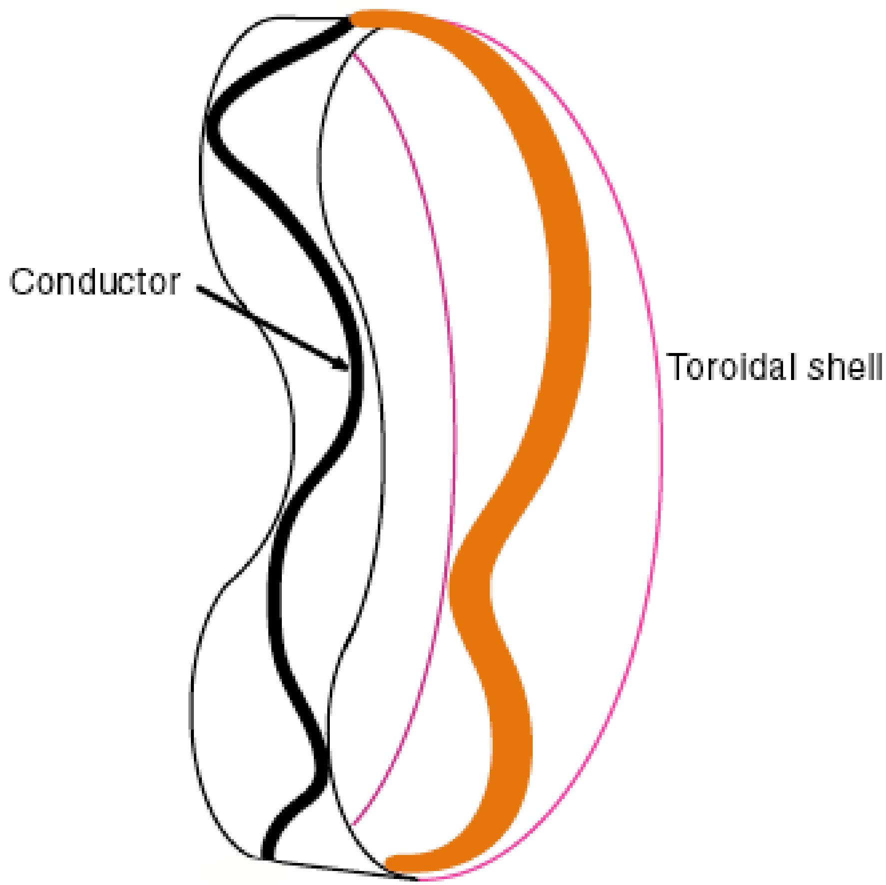
Shell coil	Radial plate coil	Hybrid coil
"Bean" shell with toroidal displacements	Bean plates warped in toroidal direction	Bean/shells warped in toroidal/poloidal direction
Capability for partially supporting out-of-plane loads	No capability for partially supporting out-of-plane loads	
Capability for partially supporting inplane loads	Decreased capability for partially supporting inplane loads	
	Fitting issues?	Fitting issues?
Need external support for inplane loads	Need larger external support for inplane loads	
Capability for conductor grading		
Very small bending radius possible	Bending radius limited by kinks in plates	

Shell coils - 1



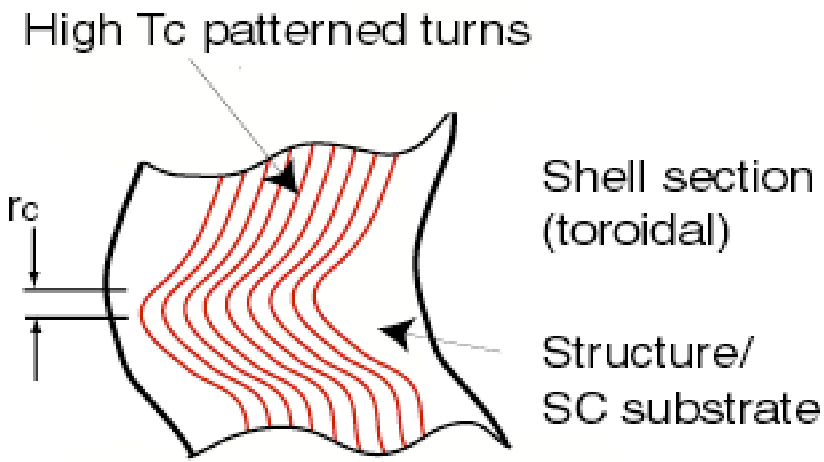
- Conductor path in toroidal shells
- Toroidal shells can be full…

Toroidal shells - 2



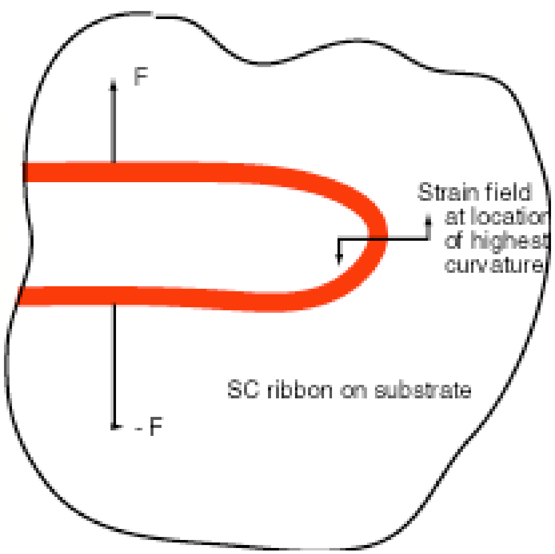
- Toroidal shells can be conforming with the conductor
  - Specially important in the outboard side/top and bottom
  - Less important on the inboard, where no access is needed

Kink radius of winding



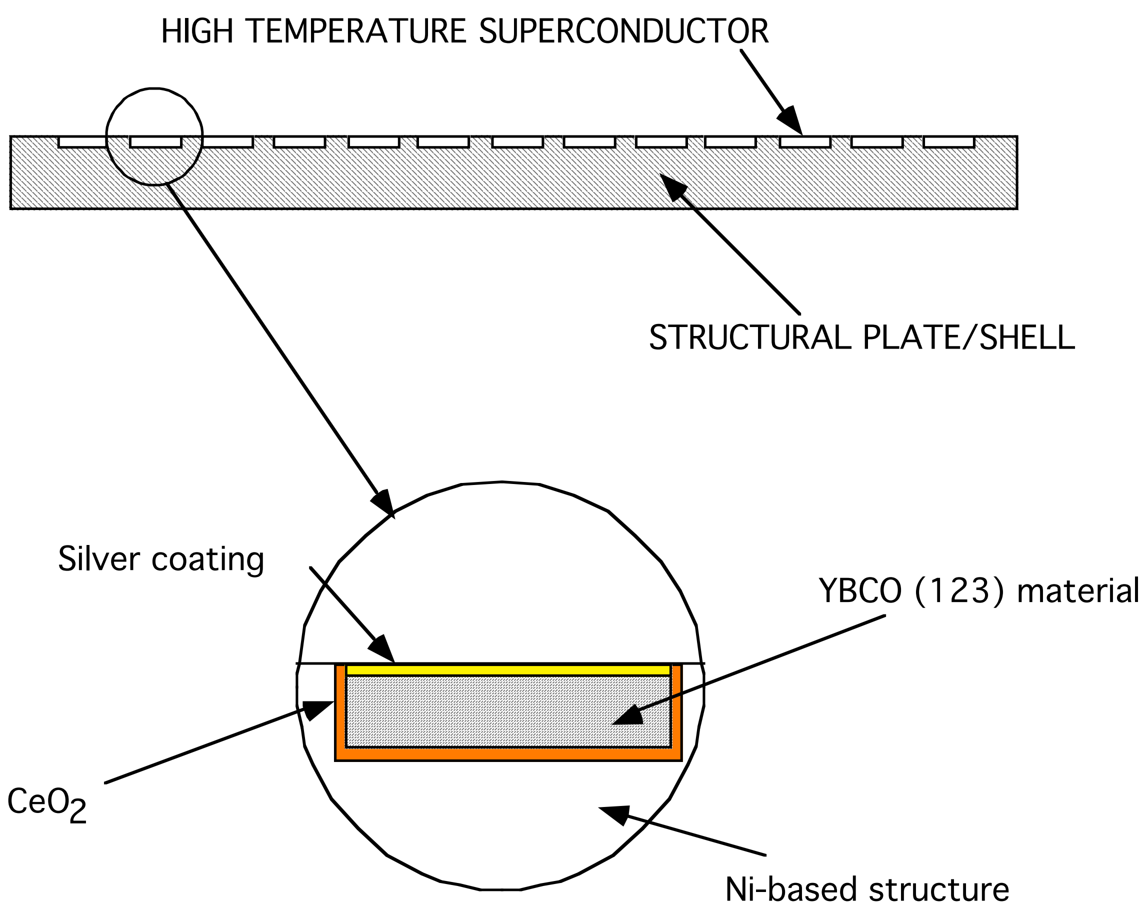
- With toroidal shells, the radius of curvature of conductor is not limited by "keystoning"
- Limit determined by strain
  - Expected to be a small effect

Strain limitations due to sharp kink



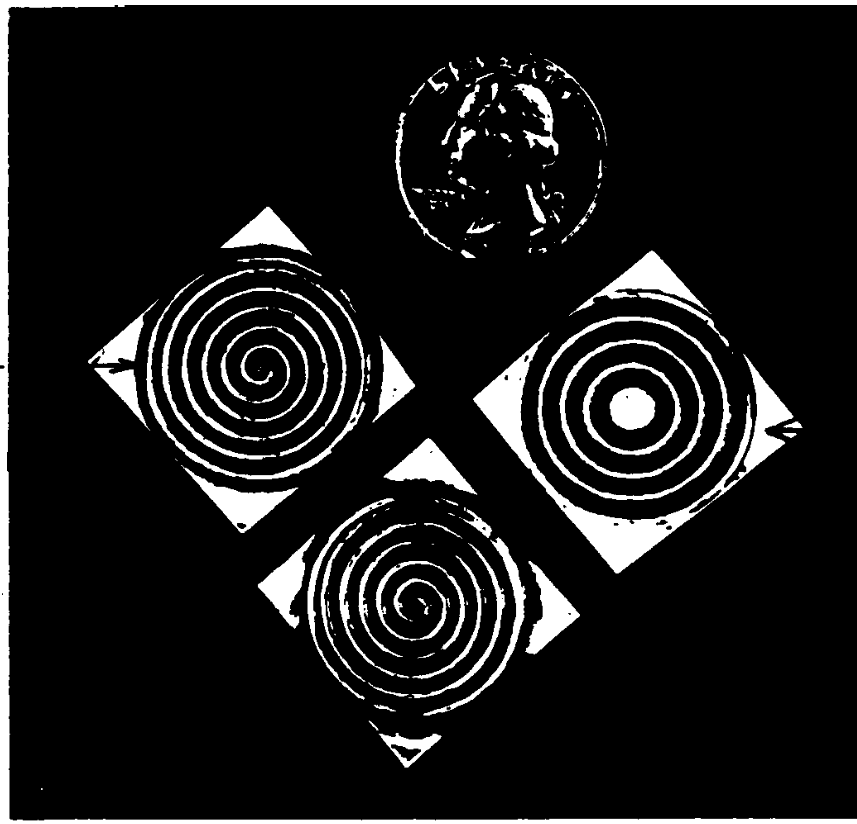
- Detailed stress calculation in progress
- Back of the envelope estimate indicates that it is not limiting
  - Largest limit at kink due to self fields

Stellerator magnet construction
Epitaxial YBCO films



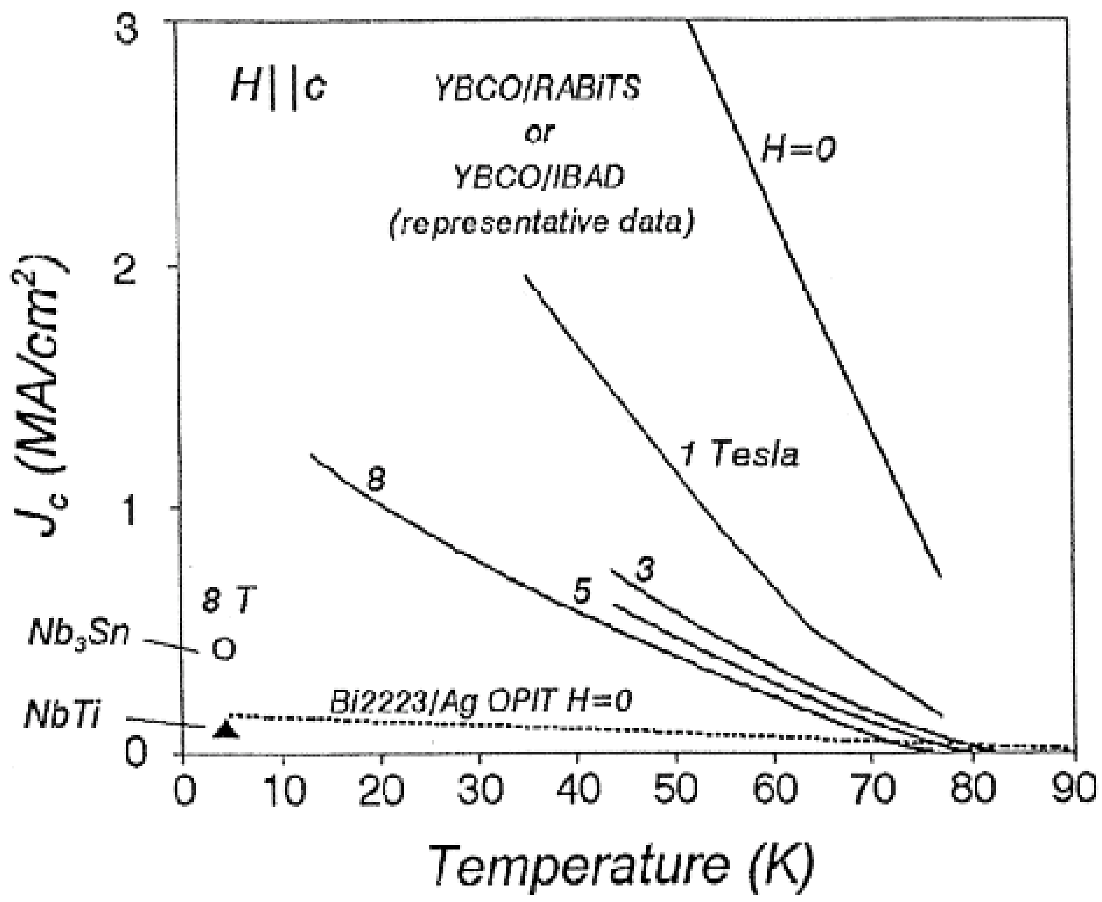
SC for modular coil-1

BSCCO 2212 layered pancakes on silver
(L. Bromberg, MIT, 1997)



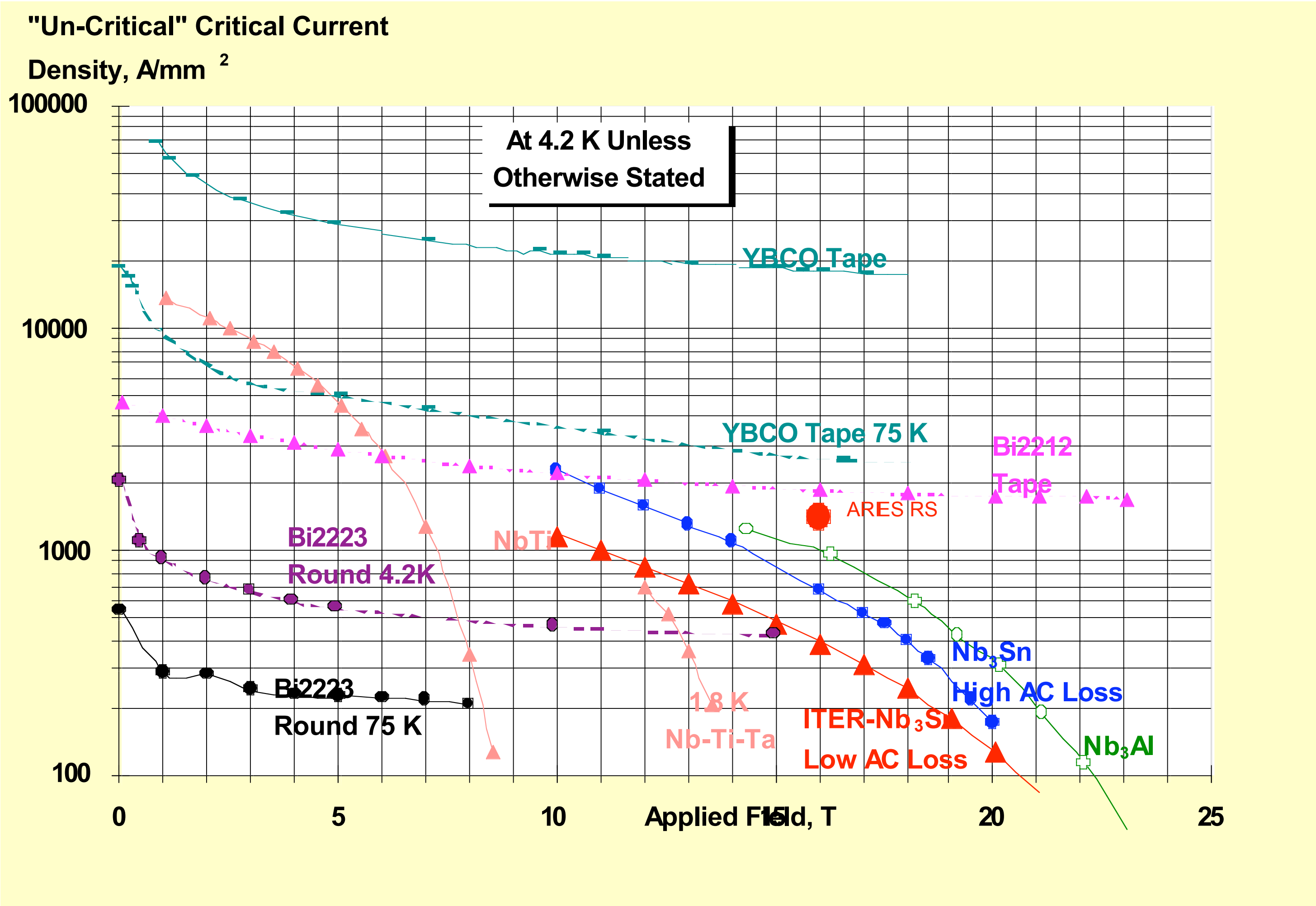
SC for modular coil-2

YBCO Current density with field in the "bad" direction (B||c) as a function of temperature



SC for modular coil-3

HTS Superconductor options and comparison with LTS (YBCO tape at 4 K and at 75 K)



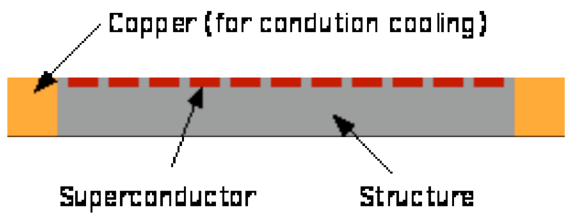
Courtesy of Lee, UW Madison

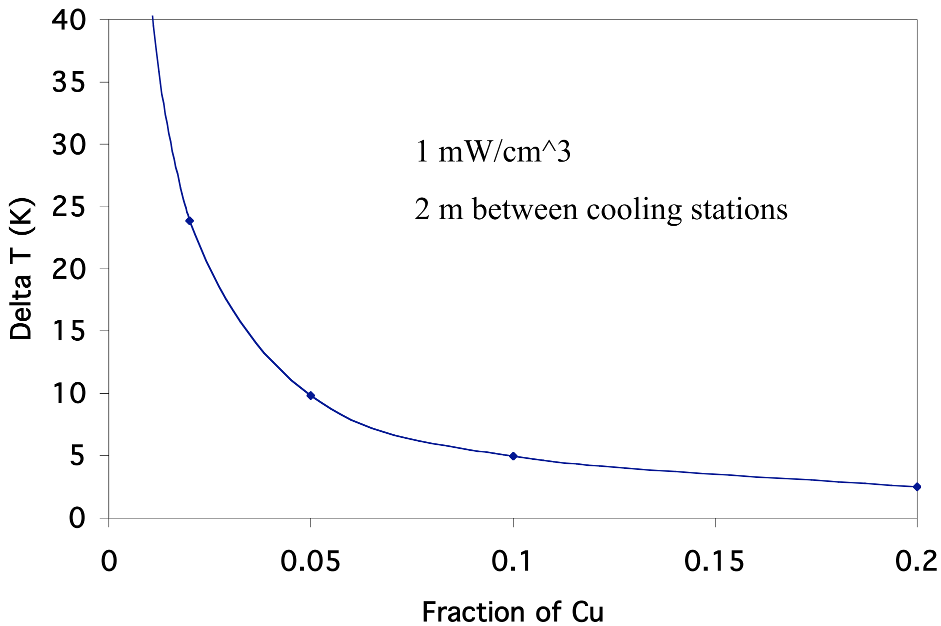
Patterned magnets

- Similar technology employed in ARIES-AT and in ARIES-IFE final focusing magnets
- Advantages over low temperature superconductors:
  - Much higher engineering current density
    - Better SC properties
    - Higher temperature of operation
    - Comparable or better irradiation properties
    - Absence of stabilizer/quench protection
    - Compatibility with epitaxial techniques
    - Use of inorganic insulator an integral part of the process

Coil Cooling (similar to ARIES-IFE)

- Assuming that quads are only cooled at each end
  - If only Ni-based material, large temperature raise midpoint between cooling stations (□T > 100 K)
  - Cu placed in parallel to structural plates (bonded at the structural plate edges, to prevent warping)





SC coil cooling-1

Structural considerations

- PF and inplane TF coil loads can be straightforwardly calculated
- TF coil out-plane loads affected by modular coils
- Modular coil loading is very complex
  - means of supporting them depend on details of the force loading
- Because of resource limitations at MIT, loading and resulting stress calculations should be performed by PPPL team.
- Because the structural plates also serve as SC substrate, strain in the SC puts an additional limitation.
  - SC strain should be limited to 0.1-0.2%

Suggested inputs for system code

- Use separate TF coils and modular coils
- For modular coils:
  - Arbitrary kink radius
  - High Tc SC, with very high current density and no need for large cross sectional fraction for quench protection/stabilizer
    - Cross sectional area, therefore, determined from structural and cooling considerations
  - Since structure is SC substrate, SC strain limitations of ~ 0.15 - 0.2% are comparable to limits in structure (~2/3 $\square_y$)
  - Allow for ~ 20% of structural cross section for cooling

Summary

- Preliminary guidelines for system code developed.
  - Design, cooling, superconductor issues in modular coil addressed

- Areas that need additional work:
  - Structural loads and support
  - Cryostat design
  - Alternative designs using low Tc
  - Alternatives to modular coil topologies
    - Helical coils???